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SUMMARY

Infrared measurements of the Spacelab 1, Space Transportation System (STS) 9, were made from the Advanced Research Projects Agency's Maui Optical Station (AMOS) tracking facility using a sensitive photometer in two infrared bands, the H-band centered at a wavelength of $1.6\ \mu\text{m}$ and the K-band centered at $2.3\ \mu\text{m}$. The objective was to measure radiation from the vicinity of the Shuttle arising from interaction of Shuttle surfaces with atmospheric particles. It was necessary to include the Shuttle itself in the field of view of the photometer. The integrated brightness of the entire Shuttle at a distance of 400 km was found to be equivalent to that of a star of magnitude +6.6 at $1.6\ \mu\text{m}$; it was much fainter in the visible. Most of the emission at $1.6\ \mu\text{m}$ appears to be attributable to the Shuttle glow phenomenon. It is hundreds of times brighter than the zodiacal background. The radiation at $2.3\ \mu\text{m}$ can be accounted for primarily by diffusely scattered thermal radiation from Earth's surface.

INTRODUCTION

A glow observed to be emanating from some surfaces of the Space Shuttle during its third flight (Banks et al. 1983) has caused concern over the intensity of any infrared emission that might accompany the phenomenon. If the glow comes from vibrationally excited OH molecules, as proposed by Slinger (1983) on the basis of an analysis by Yee and Abreu (1983) of Atmospheric Explorer photometer data, then the infrared component of the glow would be much more intense than the visible glow. A spectrum of highly excited OH calculated by Langhoff et al. (1983) shows that the spectral density could be 100 times higher at wavelengths between 1.6 and $2.0\ \mu\text{m}$ than at $0.6\ \mu\text{m}$. The importance of such radiation is that it would contribute to the foreground radiation through which infrared telescopes mounted on the Shuttle would study distant objects. This could result in erroneous measurements of extended infrared sources and extra noise in discrete sources.

The effect of the Shuttle glow phenomenon on experiments could be best determined if the sources and physical mechanisms were well understood. A definite clue comes from the observation that the Visible Airglow Experiment on board the Atmospheric Explorer (AE-E) measured a glow attributable to interaction between the spacecraft and the atmosphere that was directly proportional to the atomic oxygen density (Yee and Abreu, 1982). A compilation of photometric data at several wavelengths indicates that the spectrum rises rapidly with increasing wavelength, at least to $7320\ \text{\AA}$. Observations on Space Transportation System (STS) 4, made with a hand-held camera equipped with an objective grating (Mende et al., 1983), showed that the Shuttle glow was also brighter at longer wavelengths (up to $8000\ \text{\AA}$). On the

other hand, the thickness of the glowing region was only 5 to 20 cm whereas the thickness of the region for the Explorer was about 10 m. Because of this difference in thickness, the possibility exists that different reactions produced the glow in the two cases. The case for OH is made more convincingly for the Explorer glow (Slanger, 1983). An analysis by Hollenbach and Tielens (1984) demonstrates that the hydrogen (or some other atom or radical) that combines with the oxygen is provided by the surface materials (except those cold enough, or reactive enough, to prolong the dwell time of the incident atmospheric particles). This was demonstrated in a materials test on STS-8 (Leger, personal communication, 1984) in which the glow above oxidized aluminum was much less than that above adjacent samples of Kapton and black paint (organic binder). Adjacent Teflon had relatively little glow. Leger (1982) had observed previously that some materials, especially Kapton, deteriorated rapidly and lost a considerable amount of mass when exposed to the incident atmosphere. Presumably, the reaction products are volatiles which may leave the surfaces in excited states.

Estimates of the infrared intensity that could result from surface reactions were made by Hollenbach and Tielens (1984) on the basis of STS-3 visible glow measurements (Banks et al., 1983) and a theoretical spectrum of highly excited OH calculated by Langhoff et al. (1983). Direct measurements of the infrared intensity and spectrum from the cabin of the Shuttle are prevented by the 8000-Å transmission cutoff of the cabin windows. Instruments in the payload bay, which are designed for Earth limb or astronomical purposes, deliberately avoid looking near Shuttle surfaces where the glow appears. Since no suitable on-board instrument to study the infrared glow was available for early Shuttle missions, an approach involving ground-based facilities was devised. In this approach, a very sensitive infrared photometer and the 1.6-m telescope at the Advanced Research Projects Agency Maui Optical Station (AMOS) tracking facility were used. The STS-9 came within a few hundred kilometers of AMOS once each night of the mission. The AMOS facility is designed for the fast, accurate slew speeds needed to track satellites. A circular variable filter (CVF) spectrometer at Ames Research Center was modified to work as a broadband photometer with a field of view that was roughly matched to the size of the Shuttle at a distance of 300 km. The intensity of the entire Shuttle in two or more bands could be measured and then compared with predictions for OH or other candidate glow mechanisms. This is possible only if the Shuttle itself does not emit or scatter more radiation than the glow. In the next section of this report, the expected infrared radiation from the glow is discussed and compared with other sources of radiation in the 1- to 2.3- μ m range, where the peak intensity is expected for OH. Subsequently, the measurement technique and the observations are described and the results presented.

We are grateful to the following persons whose contributions were essential to making our mission successful: Glenn Ashley (AVCO Everett Research Laboratory, Inc.) for providing the TV camera and telescope interfaces; Joe Heath (AVCO Everett Research Laboratory, Inc.) for estimates of the visible light Shuttle brightness; R. Fisher (United States Air Force, RADC/OLAB) for coordinating our visit to AMOS, to many other members of the AMOS/Maui Optical Tracking and Identification Facility (MOTIF) staff for their cooperation and assistance; C. Osgood (Johnson Space Center)

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A PRIORI ESTIMATE OF RADIATION INTENSITY

The flux density expected from the Shuttle glow in the infrared can be estimated on the basis of the visible glow intensity observed on STS-3 and the spectrum of excited OH. The volume production rate of "visible" photon emission for STS-3 was estimated to be as high as 2×10^7 photons $\text{cm}^{-3} \text{sec}^{-1}$ within 10 cm of the ram side of the tail (Banks et al., 1983). If it is assumed that the glow comes from highly excited OH molecules, then the spectrum calculated by Langhoff et al. (1983) can be used to scale the visible photon emission rate to infrared photon emission rates for appropriate bands. Since the sensitivity of Kodak Ektachrome SO-489 film drops rapidly with wavelength at wavelengths greater than $0.68 \mu\text{m}$, and since the OH emission is negligible at wavelengths less than $0.58 \mu\text{m}$, we attribute the entire visible photon emission to the $0.58\text{--}0.68\text{-}\mu\text{m}$ band. The calculated OH spectrum then enables us to estimate the volume production rate I_λ at wavelength λ . The rate $I_{1.6}$ in our $1.6\text{-}\mu\text{m}$ "H" band (with half power points at 1.555 and $1.645 \mu\text{m}$) is about 2.0×10^9 photons $\text{cm}^{-3} \text{sec}^{-1} \mu\text{m}^{-1}$; in our $2.3\text{-}\mu\text{m}$ "K" band (2.09 to $2.49 \mu\text{m}$), $I_{2.3}$ is about 2.4×10^9 photons $\text{cm}^{-3} \text{sec}^{-1} \mu\text{m}^{-1}$. Consider the Shuttle orientation in which its long axis is parallel to its velocity vector (i.e., it flies nose first or tail first). The normal component of area A exposed to direct impact is then about $40 \times 10^4 \text{ cm}^2$. The thickness of the infrared emitting layer is the decay time τ of states from which low-lying transitions can take place (typically 10 msec) multiplied by the average component of velocity V away from the Shuttle surface (typically $2 \times 10^4 \text{ cm/sec}$) or $2 \times 10^2 \text{ cm}$. The Shuttle glow emission flux density F_λ , seen from distance ℓ , is

$$F_\lambda = I_\lambda A \tau V / 4\pi \ell^2$$

The Shuttle altitude was about 240 km for both STS-3 and STS-9, but ℓ is the total distance to the Shuttle, about $240 \text{ km} / \sin \theta$, where θ is the angle above the horizon. For $\ell = 400 \text{ km}$ ($\theta = 37^\circ$), we have $F_{2.3 \mu\text{m}} = 8 \times 10^{-19} \text{ W cm}^{-2} \mu\text{m}^{-1}$, if the assumptions made above are correct. Similarly, $F_{1.6 \mu\text{m}} = 10 \times 10^{-19} \text{ W cm}^{-2} \mu\text{m}^{-1}$. These estimates are based on a number of questionable assumptions and could be off by orders of magnitude. They are presented here only to show how the instrument requirements were chosen and to establish a basis of comparison with previous data.

The expected Shuttle glow must be compared with other sources of radiation in the same field of view. The cabin windows do not transmit significantly beyond $0.8 \mu\text{m}$, so cabin lights cannot contribute to the IR bands used in this study.

Thermal radiation from the Shuttle was originally thought to be an important contributor at longer wavelengths. The mission plan indicated that the Shuttle would be oriented with its payload bay facing Earth, so that we would observe the radiators, the warmest surfaces of the Shuttle, directly. Subsequent to the Spacelab I mission, we learned that the average radiator temperature was 286 K (Chandler, personal communication, 1984). The remainder of the Shuttle seen from Earth had an average temperature of about 250 K (Chimenti, personal communication, 1984). Thermal radiation from Earth, typically at an effective temperature of 288 K at wavelengths where the atmosphere is transparent (Johnson, 1965), scatters diffusely off of the Shuttle. In our original planning, this contribution was ignored relative to the Shuttle's thermal radiation, on the assumption that the emissivities of Earth-facing portions of the Shuttle would be near unity. Subsequently, we made laboratory measurements of the diffuse scattering properties of Shuttle surface materials at 1.6 and 2.3 μm . We examined white Shuttle tile; white, coated Nomex (used on the tops of the wings); and Teflon, which is characteristic of the payload bay and radiators. Spectra of diffusely scattered radiation from 0.65 to 2.4 μm showed that these materials act as nearly perfect diffuse reflectors in this wavelength range. (Teflon has relatively high emissivity at longer wavelengths and consequently is a good radiator near the peak of the radiator's blackbody emission curve.) Consequently, diffusely scattered thermal radiation from Earth dominates the Shuttle's 2.3- μm brightness.

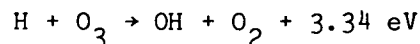
Values for flux densities of diffusely scattered thermal radiation as observed from a ground station 400 km from the Shuttle are listed in table 1. In calculating these values, the projected area of the Shuttle facing Earth was estimated to be 425 m^2 . The projection of this area normal to the line of sight from the observer was 425 $\text{m}^2 \cos 53^\circ$, since the Shuttle altitude was 240 km. Consequently, the solid angle observed from the ground was 1.6×10^{-9} sr when the Shuttle's range was 400 km. The Shuttle was assumed to be a perfect, diffuse reflector and Earth a perfect blackbody.

TABLE 1.- CALCULATED FLUX DENSITIES

Filter, μm	Scattered Earth thermal, $\text{W cm}^{-2} \mu\text{m}^{-1}$	Scattered nightglow, $\text{W cm}^{-2} \mu\text{m}^{-1}$	Expected Shuttle glow, $\text{W cm}^{-2} \mu\text{m}^{-1}$
1.6	4.7×10^{-20}	3.3×10^{-17}	1.0×10^{-18}
2.3	1.03×10^{-16}	1.8×10^{-18}	0.8×10^{-18}

Before the observations, we were not aware of the important contribution to be expected from diffuse scattering of Earth's nightglow by the Shuttle. This was pointed out to us later by D. Lemke (private communication). The irradiance of the nightglow is about 100 times greater in the infrared at 1.7 μm than in the visible (Roach and Gordon, 1973). It originates at an altitude of about 90 km and is much

brighter when this part of the atmosphere is illuminated by sunlight. The emission comes from highly excited OH produced by the reaction:



Measurements of the intensity of night sky brightness in 10 bands from 0.71 μm to 3.4 μm were made by Hofmann et al. (1978) from a balloon-borne telescope. Their values may be used to estimate the Shuttle's diffusely reflected nightglow provided that (1) we know the diffuse scattering properties of Shuttle materials, (2) we convolve the nightglow spectrum properly with our filter transmission, and (3) we perform an integration over the emitting shell of OH as seen from the Shuttle. First, our laboratory measurements of Shuttle white tile and of roughened Teflon (characteristic of the payload bay and radiators) showed that both behave as nearly perfect diffuse reflectors as noted above. Second, convolution of our filter spectral transmission with the spectrum of nightglow obtained by Hofmann et al. yields intensities of $2.0 \times 10^{-8} \text{ W cm}^{-2} \text{ sr}^{-1} \mu\text{m}^{-1}$ in our 1.6- μm band (we use their peak value at 1.7 μm) and $0.11 \times 10^{-8} \text{ W cm}^{-2} \text{ sr}^{-1} \mu\text{m}^{-1}$ in our 2.3- μm band (determined from their values at 2.1, 2.35, 2.4, and 2.45 μm). And third, an integration over the entire shell of emission (assumed 20 km thick) at an altitude of 90 km, with appropriate consideration of the longer path through parts of the shell viewed near the horizon, yielded nightglow intensities at the Shuttle of $2.06 \times 10^{-8} \text{ W cm}^{-2} \text{ sr}^{-1} \mu\text{m}^{-1}$ at 1.6 μm and $1.13 \times 10^{-9} \text{ W cm}^{-2} \text{ sr}^{-1} \mu\text{m}^{-1}$ at 2.3 μm . If the Shuttle is considered to be a perfect diffuse reflector with a solid angle of $1.6 \times 10^{-9} \text{ sr}$ (at a distance of 400 km), then the corresponding flux density observed at the ground would be $3.3 \times 10^{-17} \text{ W cm}^{-2} \mu\text{m}^{-1}$ at 1.6 μm and $1.8 \times 10^{-18} \text{ W cm}^{-2} \mu\text{m}^{-1}$ at 2.3 μm .

Thus, diffusely scattered nightglow would be the dominant source of radiation at 1.6 μm unless the Shuttle glow was much brighter than expected. The glow at 2.3 μm would have to be exceedingly bright to outshine Earth's diffusely scattered thermal emission. Clearly, observations at any longer wavelengths would be even more dominated by scattered or direct thermal emission, so the instrument chosen for the experiment had to operate in the near infrared.

INSTRUMENT CONFIGURATION

A sensitive circular variable filter (CVF) spectrometer, used previously for astronomical work (Strecker et al., 1979), was modified to provide the option of broadband photometry or CVF spectroscopy in the wavelength range from 1.2 to 2.4 μm . A schematic of the instrument is shown in figure 1. The converging f/17 beam of radiation from the 1.6-m reflecting telescope (not shown) strikes an oscillating tertiary mirror which reflects an oscillating beam onto a layer of gold on the diagonal flat labeled "beam splitter." This reflects most of the infrared radiation into the Dewar through its calcium fluoride window. The infrared light is focused as it passes through the aperture that defines the field of view to be observed. The diameter of the aperture was chosen to be 3 mm in order to provide a 24-arcsec field of view--large enough to include the whole Shuttle at distances greater than

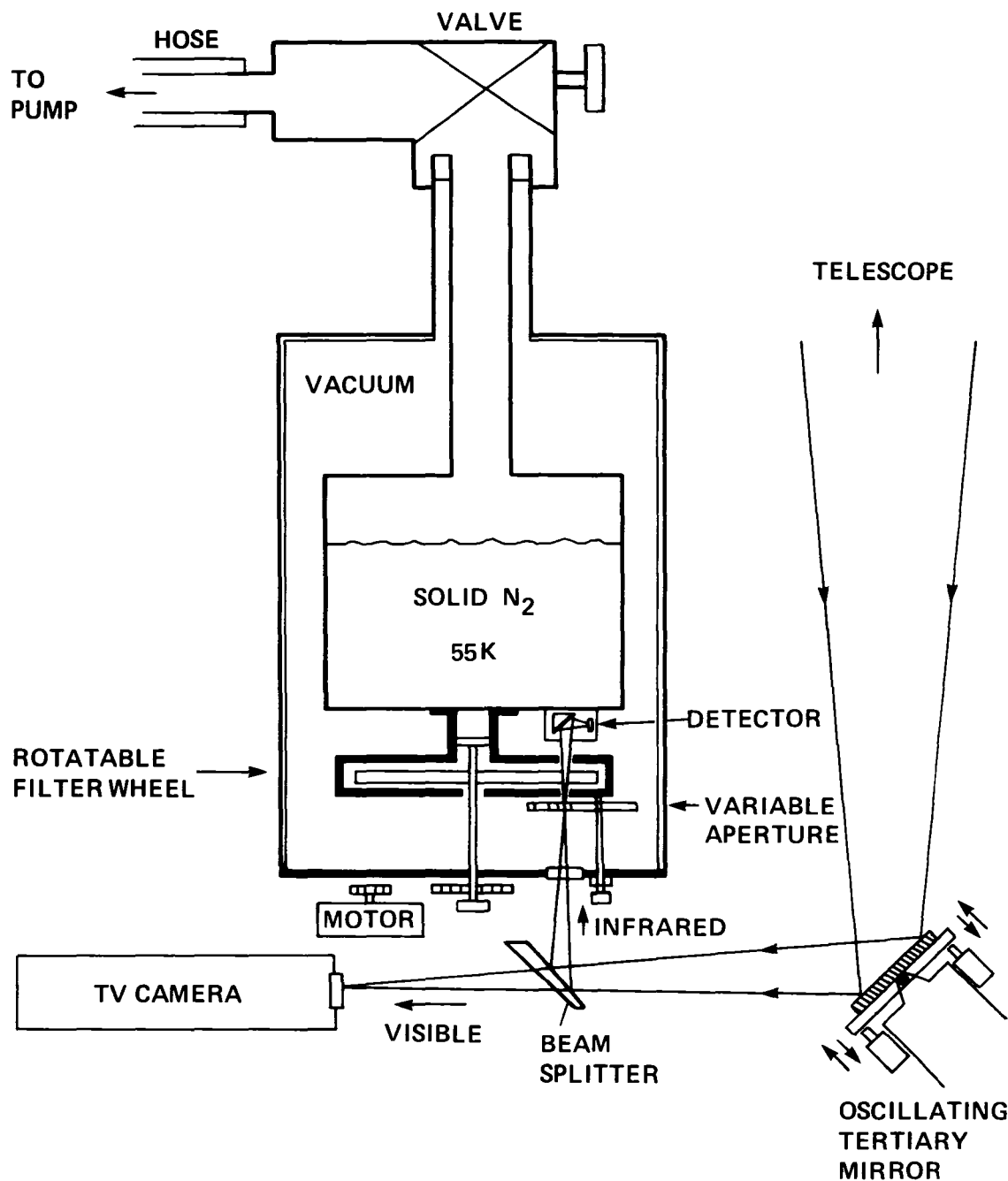


Figure 1.- Schematic diagram of focal-plane region showing cross section of CVF spectrometer/photometer.

300 km. Smaller apertures can be selected manually if one has physical access to the spectrometer. The infrared light then passes through whatever portion of the CVF or filter wheel that has been moved into its path. This motion can be controlled remotely. The wheel is seen edge-on in figure 1. The center of the wheel is displaced 1.75 in. from the optical axis so that by turning the wheel to various positions one can place various filters or parts of the CVF on the optical axis. The 1.2- to 2.4- μm CVF has a band pass of 1.5% at any point. The discrete filters permit a choice of broader band passes for higher sensitivity, as well as bands outside the CVF range. After passing through a filter, the remaining infrared energy strikes an off-axis elliptical mirror (not shown) designed to focus an image of the telescope's secondary onto the 0.5-mm-diam detector. The detector itself is indium antimonide, cooled to about 50 K by solid nitrogen. Its electrical output is connected to one gate of a dual, J-FET preamplifier in a feedback configuration described by Hall et al. (1975). Use of a high feedback resistance ($1.46 \times 10^{11} \Omega$) coupled with suitable "flashing" of the detector (illumination of the detector with 1.2- μm radiation before observation) permits noise levels of the order of $50 \mu\text{V}/\text{Hz}^{1/2}$ to be achieved in low backgrounds.

About half of the visible light is transmitted through the beam splitter and is focused on the television camera along with a projected reticle. This permits the user to boresight the telescope on a star by noting at what position the star appears on the reticle when the maximum infrared signal is observed.

Because of the oscillating beam, two star images are formed. This is a standard procedure in infrared astronomy; it permits accurate subtraction of foreground infrared radiation arising from the telescope and Earth's atmosphere. The only signal that is amplified is that which is the difference between foreground radiation, including the star (or other object), and foreground radiation without the star (or other object). Thus, the useful signal from the detector preamplifier circuit is ac. It is amplified further by a phase-lock amplifier which rejects all frequencies except those of the oscillating secondary and accepts only those at an appropriate phase determined by the observer. These signals are then recorded as a function of time on both a strip-chart recorder and a computer memory which then stores the signals as a sequential array on a floppy disk. Simultaneously, a voltage proportional to CVF position angle can be stored, properly correlated with the detector signal. This was not done, however, because only fixed filters were used to observe the Shuttle.

The instrument described here had been found in astronomical applications to have a noise-equivalent flux density of about $3.4 \times 10^{-18} \text{ W cm}^{-2} \mu\text{m}^{-1} \text{ Hz}^{1/2}$ at 2.3 μm in a 1.5% band using a telescope with a diameter of 1.6 m. The corresponding system noise equivalent power (NEP) is $1.5 \times 10^{-15} \text{ W Hz}^{-1/2}$. The available 1.6- μm filter had a 5.6% band (0.09 μm). The expected Shuttle glow at 1.6 μm using the AMOS 1.6-m-diam telescope (assuming 30% obscuration) was $1.3 \times 10^{-15} \text{ W}$, providing an expected signal-to-noise ratio (S/N) of 1 in 1 sec of integration, if we consider contributions only from the Shuttle glow.

Two conditions peculiar to the observatory required special adaptations. First, the mounting constraints at the focal plane of the telescope required that the Dewar

be upside down during much of the tracking. There was no danger of losing the cryogen, however, because the nitrogen was pumped to a solid. Since there was no vacuum line to the focal plane, we valved off the solid nitrogen reservoir just before making observations. This permitted 30 min of observation without a noticeable change in detector noise. Second, the telescope occasionally looks toward a nearby TV broadcast station. This made it essential to shield cables and avoid ground loops to avoid serious interference problems.

OBSERVATIONS AND RESULTS

The STS-9 was launched on November 28, 1983, at 6:00 a.m. HST. Its orbit precessed in such a way that it passed near Maui twice every 24 hr, once in daylight and once at night for the first 5 days of the mission. After that, all passages of STS-9 were in daylight or twilight. A practice acquisition was made in daylight on the fourth orbit using the 2.3- μm filter. Comparison with α Boo, which is magnitude -3.02 at 2.3 μm (Gehrz et al., 1974), showed that the Shuttle was of roughly the same brightness at a distance of about 400 km. This is a measure of diffuse scattered sunlight, the dominant source of luminosity in daylight at 2.3 μm . The detection was very brief, but helped to identify problems in boresighting and tracking.

The first useful nighttime passage of the STS-9 over Maui was on November 30, starting at 19:40 HST. Because of 50-mph winds, only part of the passage could be tracked. The Shuttle was held in our boresight for only 16 sec. The 2.3- μm filter was used, and a moderate signal was detected.

The night of December 2 (UT) provided the best sighting opportunity, with the Shuttle reaching a peak altitude of 74° . The strip-chart record of the track is shown in figure 2. The wide variations in signal were caused by tracking errors. All sightings were obtained during conditions of high (up to 50 mph) winds which caused tracking errors of several arcseconds. The large negative values occurred when the Shuttle was in the other beam created by the oscillating tertiary mirror-- 20 arcsec displaced from the first beam. (The direction of oscillation was perpendicular to the flight direction.) Since tracking errors can only decrease the signal, the best approximation to the signal is the envelope of peak signals minus the rms noise. The noise was determined during a practice track when the Shuttle was not in the field of view but when other conditions were similar. Calibration of the signal level was obtained by comparison with well-known stars, using magnitude and star types provided in the Yale catalogue of bright stars (Hoffleit and Jaschek, 1982). The 2.3- μm band was used throughout this passage of the Shuttle. We had hoped to switch to other infrared bands (at 1.6 and 1.3 μm) to compare intensities of different bands under similar conditions, but unfortunately, the rapid variations in signal caused by tracking errors made sequential sampling of bands useless for quantitative comparisons. Thus, we had to wait for the next night's passage to measure the 1.6- μm intensity.

On the night of December 3 (UT), the Shuttle image was acquired as it receded from Maui. Two measurements were obtained in the 1.6- μm band. The appearance of

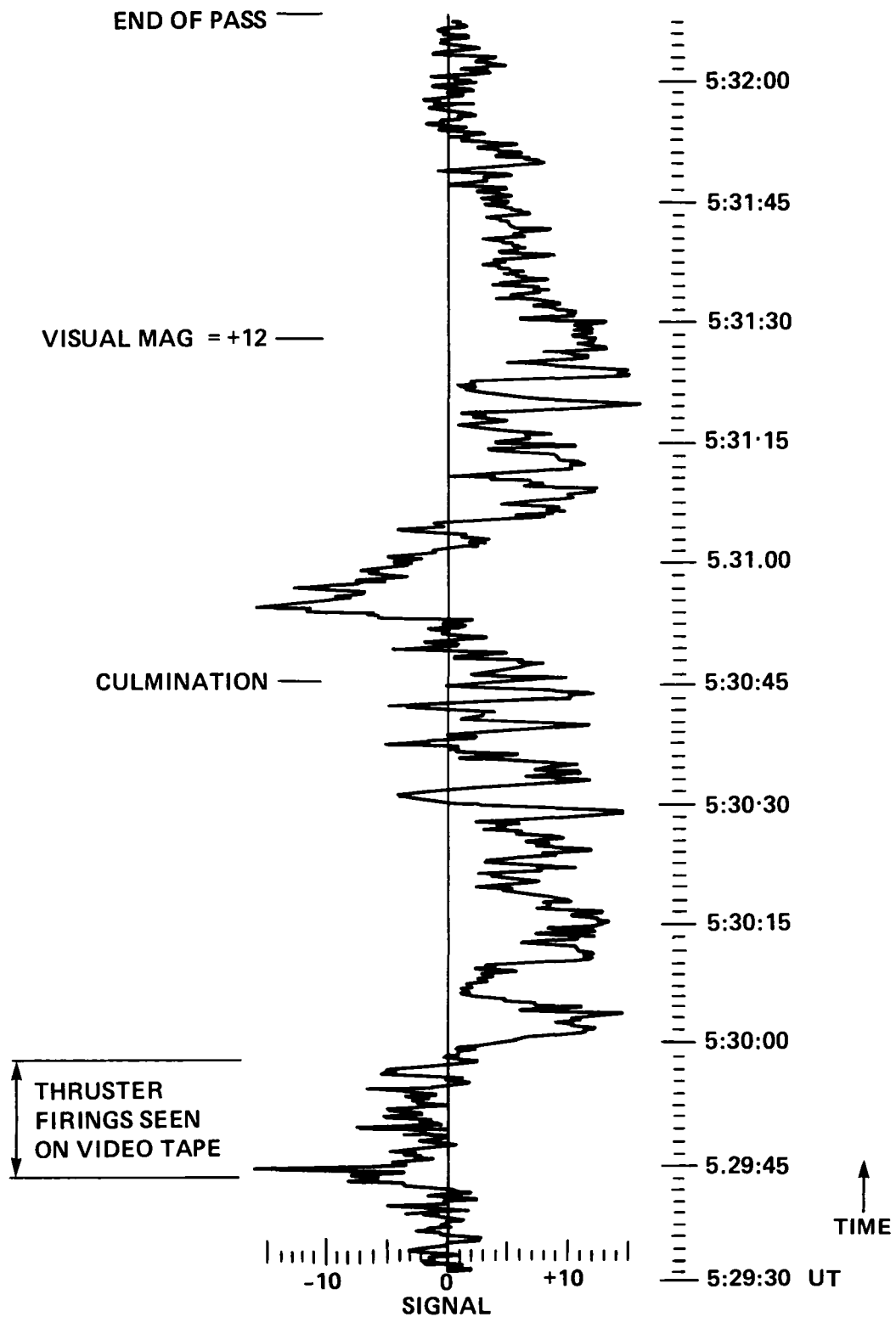


Figure 2.- Strip-chart tracing of 2.3- μ m signal versus time during Dec. 2, 1983 (UT), Shuttle sighting. Negative signals occur when Shuttle moves into opposite beam formed by the oscillating tertiary.

signals above the noise level coincided exactly with visual (TV) acquisition of the Shuttle by the tracker operator, as was the case in the previous measurements. A summary of all the nighttime measurements is given in table 2. The distances to the Shuttle were determined by the AMOS computational facilities from updated Shuttle orbital parameters. The field of view is given in meters at the distance of the Shuttle for comparison with the overall Shuttle length of 35 m. According to the STS-9 flight plan (Spacelab 1 Flight Definition Document, 1983), all observations given in table 2 (except for 1 Dec., UT) were made with the Shuttle in the -Z/N, -X/VV configuration (i.e., long axis in the velocity vector, payload bay facing Earth, nose pointed opposite the velocity vector). During the 1 Dec. (UT) pass, the Shuttle was in the "hot test configuration" (i.e., the payload bay was normal to the Sun's rays, long axis parallel to the terminator and nose pointed north).

TABLE 2.- RESULTS OF STS-9 NIGHTTIME PHOTOMETRY

Date and time (1983)		(3) Band ^a	(4) Magnitude	(5) Flux density, $10^{-16} \text{ W cm}^{-2} \mu\text{m}^{-1}$	(6) Range, ^b km	(7) (Flux density) $\times (\text{range}/400 \text{ km})^2$, $10^{-16} \text{ W cm}^{-2} \mu\text{m}^{-1}$	(8) Field of view, m
(1) Hawaii standard h m s	(2) Universal h m s						
Nov 30 19 39 34	Dec 1 5 39 34	K	6 24	1.24	574 A	2 6	67
Dec 1 19 30 03	Dec 2 5 30 03	K	6 4	1 1	409 A	1 15	48
19 30 16	5 30 16	K	6 3	1 2	340 A	87	40
19 31 24	5 31 24	K	6 1	1 4	376 R	1 24	44
19 31 27	5 31 27	K	6 38	1 09	400 R	1 09	47
30	30						
19 31 49	5 31 49	K	6 9	65	530 R	1 14	62
19 32 02	5 32 02	K	7 8	3	611 R	70	71
Dec 2 19 21 00	Dec 3 5 21 00	H	6 86	2 0	450 R	2 5	52
19 21 25	5 21 25	H	7 1	1 6	593 R	3 5	69

^aH = 1.6 μm , K = 2.3 μm

^bA = approaching, R = receding

More observations of the STS-9 were made in daylight on the mornings of December 6 and 7. On December 6, at 1735:30 UT, the flux observed at 2.2 μm was $2.7 \times 10^{-13} \text{ W cm}^{-2} \mu\text{m}^{-1}$ at a distance of 240 km. On December 7, the maximum observed flux at 2.2 μm was $3.3 \times 10^{-13} \text{ W cm}^{-2} \mu\text{m}^{-1}$ at a distance of 315 km. The intensities observed in daylight are dominated by scattered sunlight; they provide no information about oxygen glow, but were useful in verifying the telescope's tracking characteristics.

DISCUSSION

The Shuttle's nighttime brightness at $1.6\ \mu\text{m}$ was much greater than expected from diffusely scattered nightglow. At $2.3\ \mu\text{m}$ it was about what one should expect from diffusely scattered thermal emission from Earth. After subtraction of the calculated nightglow (table 1), the flux density attributable to infrared Shuttle glow at $1.6\ \mu\text{m}$ was $2.2 \times 10^{-16}\ \text{W cm}^{-2}\ \mu\text{m}^{-1}$, about 220 times the value extrapolated from STS-3. These results are listed in table 3. To compare them with zodiacal irradiance we divide by the approximate solid angle of the radiating area. The solid angle is simply assumed to be twice that of the Shuttle at 400 km. The maximum possible solid angle from which the detected flux came would be the $1.08 \times 10^{-8}\ \text{sr}$ allowed by the instrument field of view. This is 6.8 times the Shuttle's solid angle at 400 km, so the irradiance could be 3.4 times smaller than the value in table 3 if the glow is very extended. We have very little data to suggest the extent of the glow. One indication comes from column 7 of table 2 where the flux density is adjusted to the distance at 400 km by multiplying by $(R/400\ \text{km})^2$. If the object is totally within the field of view, the result should be a constant throughout any one sighting (provided that the projected area of the radiating source is the same). If the source of radiation extends beyond the field of view when the Shuttle is nearest, then the flux density will drop off more slowly than R^{-2} as the Shuttle recedes, because the linear field of view (column 8, table 2) is getting larger and encompassing more of the radiating region. There is a suggestion of this in the Dec. 3 (UT) results, but they are accurate to only 20%, and values at only two distances were obtained. The results from Dec. 2 (UT) are irrelevant to this argument because they were obtained at $2.3\ \mu\text{m}$, a band in which diffusely scattered thermal radiation from Earth accounts for all the observed signal. If the Dec. 2 (UT) values in column 7 are adjusted to cancel the effect of the change in the projected solid angle of the Earth-facing portions of the Shuttle, then these values should be independent of range, R . This adjustment is done by dividing each value in column 7 by $\cos^{-1}(240\ \text{km}/R)$. The result is fairly independent of R , consistent with Lambertian

TABLE 3.- SHUTTLE GLOW IN THE INFRARED

Wavelength, μm	Best measured flux density (400-km range), $\text{W cm}^{-2}\ \mu\text{m}^{-1}$	Flux density minus scattered radiation (table 1), $\text{W cm}^{-2}\ \mu\text{m}^{-1}$	Estimated irradiance of Shuttle glow (at 240 km altitude), $\text{W cm}^{-2}\ \mu\text{m}^{-1}\ \text{sr}^{-1}$	Zodiacal irradiance, ^a $\text{W cm}^{-2}\ \mu\text{m}^{-1}\ \text{sr}^{-1}$
1.6	2.5×10^{-16}	2.2×10^{-16}	6×10^{-8}	2.4×10^{-11}
2.3	1.09×10^{-16}	Negligible	Negligible	7×10^{-12}

^aBased on data of Nishimura (1973), extrapolated to 90° from Sun in ecliptic plane using Allen (1973).

scattering from the Shuttle itself. This, in turn, is consistent with the assignment of all the 2.3- μ m flux to diffusely scattered thermal radiation from Earth.

The large discrepancy between the 1.6 μ m flux density measured for STS-9 and those extrapolated from STS-3 visible-light spectra can be explained in any of the following three ways. First, the ratio of IR to visible emission could be much higher than the model used by Langhoff for OH. This could happen, for instance, if the OH was not as highly excited as assumed. Alternately, other molecules could be involved. Second, the surfaces impacted by the atmospheric oxygen during our observations could have been more reactive than those observed from the cabin. And three, the assumptions involved in estimating the visible photon volume density and its bandwidth could be in error. This is potentially a source of large error because the sensitivity of photometric film and the cabin window transmission drop rapidly with increasing wavelength in the spectral range of the visible light emission, which rises rapidly with increasing wavelength.

Another possibility, of course, is that our own interpretation of what we observed could be in error. For example, if the thrusters were firing intermittently throughout all of the observations in table 2, our readings would have been measurements of rocket exhaust instead of Shuttle glow. Such firings were not called for in the mission plan. Furthermore, the visible flashes from firings could be seen on the TV, and they were not coincident with any of the data points used in table 2. Eventually, we expect to receive a record of actual firing times, so that this point can be verified. Another possibility is that sunlight scattered in the atmosphere reached the Shuttle. Note that the Shuttle was not in direct sunlight during any of the observations listed in table 2. Furthermore, on Dec. 2 and 3 (UT) our observations were made from east of the Shuttle, so we were seeing its darker side. Visible-light estimates of the Shuttle's brightness were made after the Dec. 2 (UT) flight by comparison of videotaped Shuttle images with star images of known magnitude, defocused to give the same image size as the Shuttle.

Although the videotape is unavailable for Dec. 3 (UT) when the 1.6- μ m observation was made, there is a portion of the Dec. 2 tape obtained at 5:29:50 UT when the lighting conditions of the Shuttle were very similar to those at 5:21:25 UT on Dec. 3 when the last 1.6- μ m observation was made. The observed visible magnitude (after correction for the transmission of our beam splitter) was 10 to 10.5. Sunlight scattered by the upper atmosphere would be roughly the same magnitude at 1.6 μ m as at visible, so the contribution of atmospherically scattered light to the Shuttle's 1.6- μ m brightness appears to be of the order of 6%. Another consideration is the variability of the nightglow.

Observations by Huppi and Stair (1969) show that the OH contribution to nightglow, which accounts for all of its 1.6- μ m intensity, varies by less than a factor of 2 throughout the night and twilight. This is in sharp contrast to the excited atomic oxygen emissions which vary by factors of 10 or more. Long-term variations in the nightglow intensity at 1.6 μ m may be possible, although we have seen no evidence to suggest that they would be large enough--a factor of 7 increase over the results of Hofmann et al. (1978)--to account for our observed flux densities at 1.6 μ m.

Further measurements of a satellite at different times would help to clarify this point.

The large production of infrared photons found in this measurement is inconsistent with the much smaller theoretical estimates for inert surfaces made by Hollenbach and Tielens (1984). This suggests a very reactive surface and raises the possibility that unburned rocket fuel (monomethyl hydrazine) from the vernier thrusters is coating much of the outer Shuttle surface. It is well known that 10% of the ejected material is unburned fuel and that two of the aft Vernier thruster exhausts impinge on the aft body flap. This could be instrumental in spreading reactive material over much of the Shuttle's rear which, incidentally, was in the ram direction during all of our nighttime observations. A better assessment of the source of the reactive material will require further observations of the Shuttle in different attitudes, spectroscopic observations to identify the radiating species, and possibly, laboratory measurements of the infrared photons that are produced when rocket fuel is bombarded by atomic oxygen. Comparisons of the 1.6- μm irradiance when the Shuttle has its nose in the ram direction with its irradiance when the aft section is in the ram direction will be especially important.

Finally, we must emphasize the serious implications of the results shown in table 3. If we assume that the 1.6- μm irradiance is proportional to the atomic oxygen flux, then the irradiance at an altitude of 400 km (typical for a Shuttle-based observatory) will be about $5 \times 10^{-9} \text{ W cm}^{-2} \mu\text{m}^{-1} \text{ sr}^{-1}$. This is about 200 times the zodiacal irradiance. This excessive irradiance will increase noise about 15-fold near 1.6 μm . If OH is the source, then astronomical observations could be seriously impaired between 1 and 4 μm and may be affected out to 15 μm .

CONCLUSION

The nighttime emitted flux from the STS-9 at 1.6 μm is much higher than can be accounted for by the Shuttle's thermal radiation or by scattered radiation from Earth or its atmosphere. We conclude that this excess radiation is attributable to the Shuttle-glow phenomenon. If this conclusion is correct, then the infrared "sky" over the Shuttle's bay would be 200 times brighter than the zodiacal background at a Shuttle altitude of 400 km and brighter yet at lower altitudes. Although the relative values of visible, 1.6- μm , and 2.3- μm measurements are roughly consistent with the emission spectrum of highly excited OH, other possibilities have not been fully examined. In any case, the material being oxidized has not been isolated. Examination of Shuttle emission spectra obtained with a variety of Shuttle attitudes may be needed to determine the identity of the emitting molecules and their source.

REFERENCES

- Allen, C. W.: *Astrophysical Quantities*. Third ed. The Athlone Press, University of London, 1973, p. 159.
- Banks, P. M.; Williamson, P. R.; and Raitt, W. J.: Space Shuttle Glow Observations. *Geophys. Res. Lett.*, vol. 10, 1983, p. 118.
- Gehrz, R. D.; Hackwell, J. A.; and Jones, T. W.: IR Observations of Be Stars from 2.3-19.5 μm . *Astrophys. J.*, vol. 191, 1974, p. 675.
- Hall, D. N. B.; Aikens, R. S.; Joyce, R.; and McCurnin, T. W.: Johnson Noise Limited Operation of Photovoltaic InSb Detectors. *Appl. Opt.*, vol. 14, 1975, p. 450.
- Hoffleit, D.; and Jaschek, C.: *The Bright Star Catalogue*. Yale University Observatory, New Haven, Conn., 1982.
- Hofmann, W.; Lemke, D.; and Frey, A.: Mapping of the Galactic Center and the Aquila Region in the Near Infrared from Balloon Altitudes. *Astron. Astrophys.*, vol. 70, 1978, pp. 427-429.
- Hollenbach, D.; and Tielens, A. G. G. M.: Infrared Emission Associated with Chemical Reactions on Shuttle and SIRTf Surfaces. NASA TM-85875, 1984.
- Huppi, E. R.; and Stair, A. T., Jr.: Sunset to Sunrise Variations of the OH Emission of the Night Sky. *Atmospheric Emissions*, B. M. McCormac and A. Omholt, eds., Van Nostrand Reinhold Company, New York, 1969, pp. 471-475.
- Johnson, F. S.: *Satellite Environment Handbook*. Stanford University Press, Stanford, Calif., 1965, p. 147.
- Langhoff, S. R.; Jaffe, R. L.; Yee, J. H.; and Dalgarno, A.: The Surface Glow of the Atmospheric Explorer C and E Satellites. *Geophys. Res. Lett.*, vol. 10, 1983, p. 896.
- Leger, L. J.: Oxygen Atom Reactions with Shuttle Materials at Orbital Altitudes. NASA TM-58246, 1982.
- Mende, S. B.; Garriott, O. K.; and Banks, P. M.: Observations of Optical Emissions on STS-4. *Geophys. Res. Lett.*, vol. 10, 1983, p. 122.
- Nishimura, T.: *Infrared Spectrum of Zodiacal Light*. Publ. Astron. Soc. Japan, vol. 25, 1973, p. 375.
- Roach, F. E.; and Gordon, J. L.: *The Light of the Night Sky*. D. Reidel Publishing Company, Boston, 1973.

Slanger, T. G.: Conjectures on the Origin of the Surface Glow of Space Vehicles. Geophys. Res. Lett., vol. 10, 1983, p. 130.

Spacelab 1 Flight Definition Document Summary. Publication JA-024, NASA Marshall Space Flight Center, Ala., 1983.

Strecker, D. W.; Erickson, E. F.; and Witteborn, F. C.: Airborne Stellar Spectrophotometry from 1.2 to 5.5 Microns: Absolute Calibration and Spectra of Stars Earlier than M3. Astrophys. J., Suppl. Ser., vol. 41, 1979, p. 501.

Yee, J. H.; and Abreu, V. J.: Optical Contamination on the Atmosphere Explorer-E Satellite. Proc. Soc. Photo-Opt. Instrum. Eng., vol. 338, 1982, p. 120.

Yee, J. H.; and Abreu, V. J.: Visible Glow Induced by Spacecraft-Environment Interaction. Geophys. Res. Lett., vol. 10, 1983, p. 126.

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16 Abstract Infrared measurements of the Spacelab 1, Space Transportation System (STS) 9, were made from the Advanced Research Projects Agency's Maui Optical Station (AMOS) tracking facility using a sensitive photometer in two infrared bands, the H-band centered at a wavelength of 1.6 μm and the K-band centered at 2.3 μm . The objective was to measure radiation from the vicinity of the Shuttle arising from interaction of Shuttle surfaces with atmospheric particles. It was necessary to include the Shuttle itself in the field of view of the photometer. The integrated brightness of the entire Shuttle at a distance of 400 km was found to be equivalent to that of a star of magnitude +6.6 at 1.6 μm ; it was much fainter in the visible. Most of the emission at 1.6 μm appears to be attributable to the Shuttle glow phenomenon. It is hundreds of times brighter than the zodiacal background. The radiation at 2.3 μm can be accounted for primarily by diffusely scattered thermal radiation from Earth's surface.			
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